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Signal/Image Processing of Acoustic Flaw Signatures for Detection and Localization

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The timely, nondestructive evaluation (NDE) of critical optics in high energy, pulsed laser experiments is a crucial analysis that must be performed for the experiment to be successful. Failure to detect flaws of critical sizes in vacuum-loaded optical windows can result in a catastrophic failure jeopardizing the safety of both personnel and costly equipment. We discuss the development of signal/image processing techniques to both detect critical flaws and locate their position on the window. The data measured from two orthogonal arrays of narrow beamwidth ultrasonic transducers are preprocessed using a model-based scheme based on the Green's function of the medium providing individual channel signatures. These signatures are then transformed to the two-dimensional image space using a power-based estimator. A 2D-replicant is then constructed based on the underlying physics of the material along with the geometry of the window. Correlating the replicant with the enhanced power image leads to the optimal 2D-matched filter solution detecting and localizing the flaw. Controlled experimental results on machined flaws are discussed.

INTRODUCTION

In high-energy laser-based, physics experiments, the extreme fluence levels employed in the laser beams can damage the inherent optical components. These damage sites, or flaws, take the form of pits in the surface of the optic with cracks radiating towards its interior. Of great concern is the risk to both personnel and equipment posed by the failure of stress loaded optics.

An acoustic measurement system using high frequency ultrasound (5 MHz) is developed to insonifiy the optic and acquire reflections from surface pits, [1,2]. Coupled to the development of custom NDE hardware, we develop novel signal/imaging techniques that detect and localize defects in these laser optics [3]. Once detected, localization of the defect position within the material is performed. It is important to understand that most materials, especially component optics, have many small defects distributed throughout, so it is necessary that the localizer help select the strongest returns. A technique that creates an image of the component emphasizing the largest defects is developed to determine the overall integrity of the part. The square shape of the vacuum window greatly influences the design of the measurement system. Employing the principle of intersecting orthogonal beams, the ultrasonic system uses a total of 34 sensors arranged in two arrays of 17 sensors. To achieve orthogonality, these two arrays of transceivers are mounted on adjacent sides of the optic: one mounted on the top and the other mounted on the left side as shown in Fig. 1. The sensors in the combined arrays are excited sequentially in a pulse-echo mode. The component transducers are selected with very narrow beamwidths. Conceptually, this approach, using orthogonal acoustic beams, will yield two measurements of each flaw: one from the left side and one from the top. These two measurements can then be used to detect and characterize a flaw.

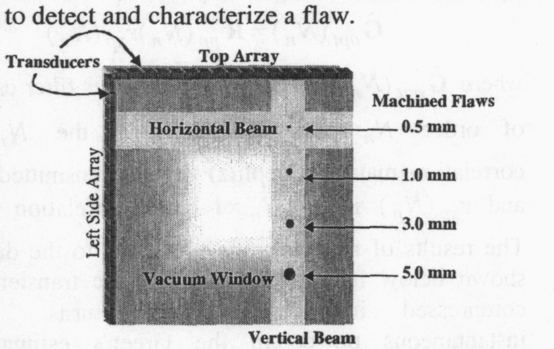

FIGURE 1. Acoustic arrays mounted on the left side and the top with orthogonal directed beam patterns.

Our processing approach exploits the orthogonality of the multi-channel array data to create a two dimensional image of the optic. An iterative search of the image is used to detect and localize each flaw. A list of flaw locations is incrementally constructed after each iteration of the search algorithm.

SIGNAL/IMAGE PROCESSING

Next we discuss the signal and image processing needed to perform the detection and localization. Before a two dimensional image can be created, the multi-channel array data received from the ultrasonic measurement system must be preprocessed. This processing involves several sequential steps to sharpen critical features of the flaw's signals, while negating the undesirable contributions of noise, clutter and ghosts.

The received signal results from the transmitted ultrasound pulse as it propagates through the glass, convolves with a flaw and is scattered back to the receiver. Assuming that the optical window is a homogeneous medium, the Green's function can be represented by a set of point scatterers (returns) with corresponding attenuation, α_i, and time delays, τ_i. Using this model to this data yields the data measured at each sensor

$$x_m(n) = \sum_i \alpha_i \delta(n-\tau_i) * p_m(n) = \sum_i \alpha_i p_m(n-\tau_i) \quad (1)$$

where $x_m(n)$ is the received measurement and $p_m(n)$ is the original ultrasonic pulse transmitted from the m^{th} transmitter.

Thus, the time delay estimation problem can be transformed to the problem of estimating the homogeneous Green's function from the noisy data. This problem is solved channel-by-channel. Therefore the best estimate of the Green's function in a mean-squared error sense is given by [3]

$$\hat{\mathbf{G}}_{opt}(N_n) = \mathbf{R}_{pp}^{-1}(N_n)\mathbf{r}_{xp}(N_n) \quad (2)$$

where $\hat{\mathbf{G}}_{opt}(N_n)$ is the optimal Wiener filter estimate of order N_n and $\mathbf{R}_{pp}(N_n)$ is the $N_n \times N_n$ correlation matrix (Toeplitz) of the transmitted pulse and $\mathbf{r}_{xp}(N_n)$ is the $N_n \times 1$ cross–correlation vector. The results of applying this processor to the data are shown below in Fig. 2b. Clearly the transients are compressed into impulse-like returns. The instantaneous power in the Green's estimates is computed by sliding a window through the channel time series calculating the power as shown in Fig. 2c.

Finally, a power image is created by interpolating the multi-channel time series to be equi-dimensional images, normalizing (unit variance) and combining the array images. Fig. 3 shows the power image for the data of Fig. 1. Note that the intersection of horizontal and vertical bars identifies a flaw in the window. Next a 2D-matched filter [3] is constructed after converting the power to a binary image increasing the signal-to-noise ratio and creating a physics-based replicant based on the geometry of the window. Cross-correlating the binary image (*B*) with the replicant (*M*) yields the

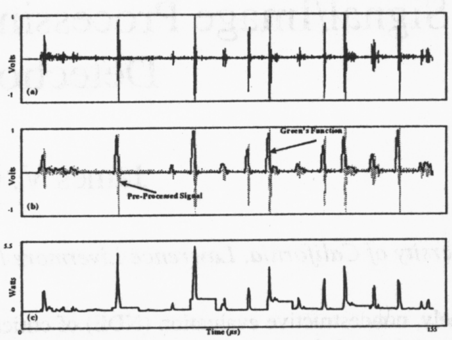

FIGURE 2. Channel preprocessing: (a) Raw channel data. (b) Green's function estimation. (c) Power estimation.

matched filtered output

$$R_{MB}(j,k) = R_{MM}(j-p, k-q), \max R_{MB} = R_{MM}(0,0)$$

implying that a peak occurs when $j=p, k=q$. The flaws are detected iteratively by sequentially detecting a peak, localizing its position spatially, nulling that section of the corresponding time series and repeating the process until all flaws are removed. We show the result of the 2D-matched filter output in Fig. 3 for the dominant flaw in the window. This completes the processing with both flaw detection and localization achieved.

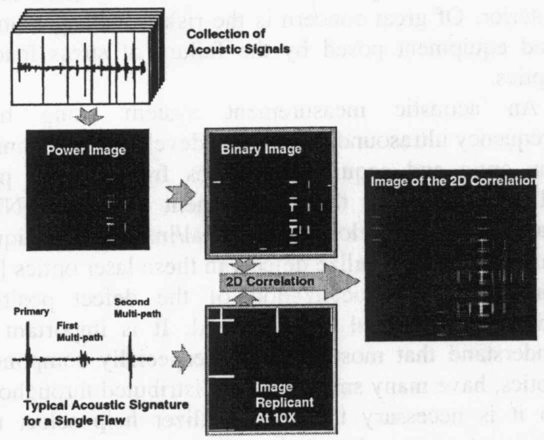

FIGURE 3. Power image estimation and 2D matched-filter output for flaw detection and localization.

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